

**DRAFT October 1999**

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# **INTEGRATED NATIONAL ASSESSMENT OF HYPOXIA AND EUTROPHICATION**

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developed for

The National Science and Technology Council  
Committee on Environment and Natural Resources  
Task Force on Harmful Algal Blooms and Hypoxia



*Cyanobacteria bloom in Potomac River. This bloom may eventually lead to low dissolved oxygen in bottom waters when the algae sinks to the bottom and decays.*

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# Introduction

The intent of this assessment is to summarize the current knowledge of the status and trends of hypoxia in coastal water, to provide a range of alternatives for addressing hypoxia and other nutrient and eutrophication related water quality problems, and to evaluate costs and benefits of these alternatives.

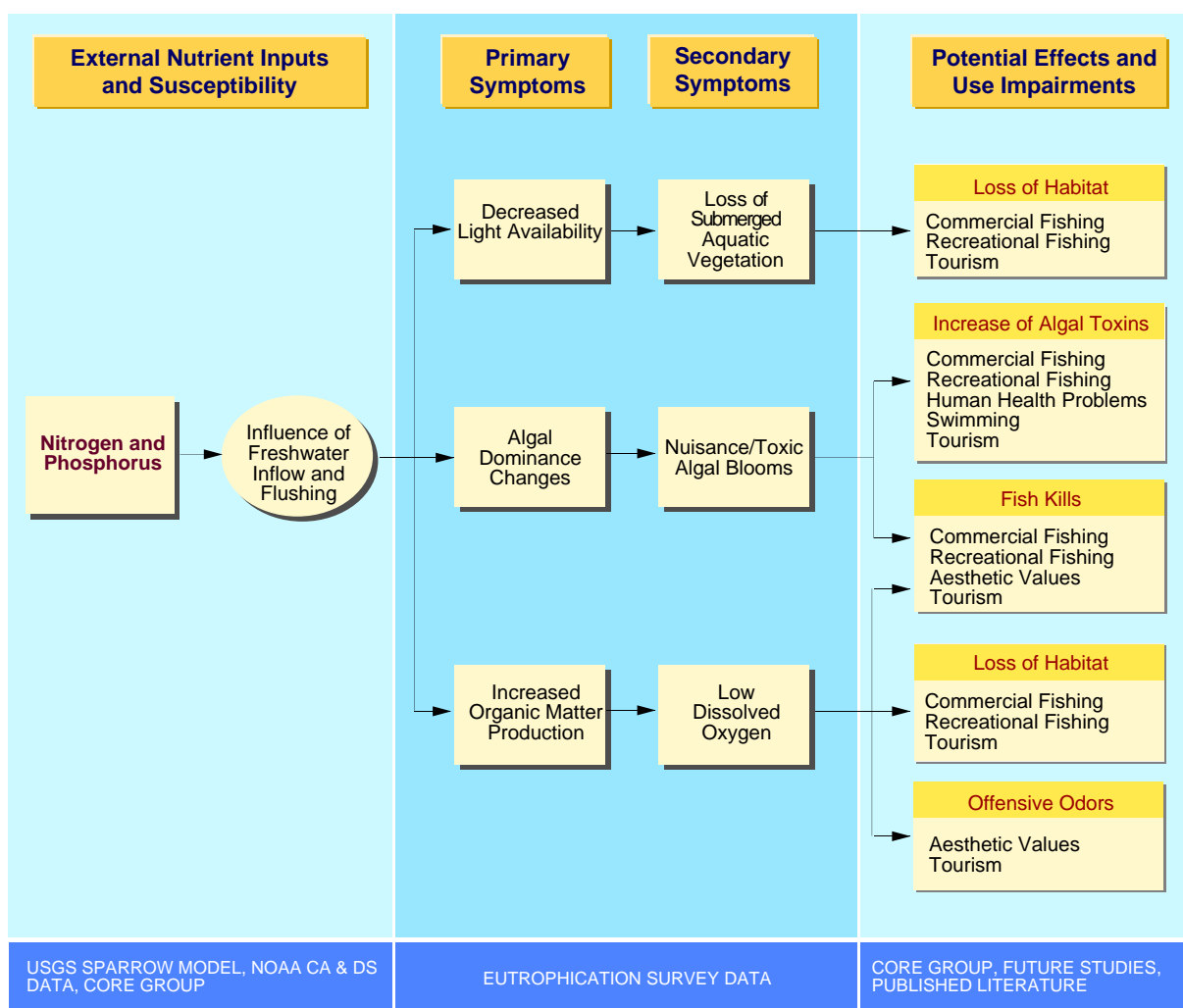
## What is hypoxia?

Hypoxia refers to a deficiency of oxygen. In humans, hypoxia is a deficiency of oxygen in the blood that leads to oxygen deprivation in body tissues. In estuarine and coastal waters the definition is similar, referring to a deficiency of oxygen typically in bottom waters that causes, among other things, physiological stress and sometimes death to aquatic organisms. For both humans and waterbodies, hypoxia is an indication of degraded health, even though there is still a low concentration of oxygen in the system. Anoxia, on the other hand, connotes a total lack of

oxygen and is a much more serious condition.

In much the same way that oxygen concentration in a persons blood is used as an indication of health, one of the traditional measures of the health of coastal waterbodies is the concentration of dissolved oxygen. Specifically, hypoxia and anoxia are used as indicators of the condition, or health, of a waterbody in relation to nutrient inputs. However, dissolved oxygen concentrations are indirect indicators of excessive nutrient inputs, and are only one of a suite of symptoms that can be used to monitor or track the health of

**Figure 1. Eutrophication Model.** Note that low dissolved oxygen is not a direct response to nutrient inputs but rather is a symptom that follows a progression that begins with nutrient inputs. The direct response is elevated algal production (the first indication that there may be a problem with nutrient enrichment) that may cause low dissolved oxygen conditions in bottom waters. Note also that there are other symptoms, loss of Submerged Aquatic Vegetation (SAV) and occurrences of nuisance and toxic algal blooms, that indicate a more advanced nutrient enrichment problem.



waterbodies in relation to nutrient enrichment. This array of symptoms, including hypoxia and anoxia, are indicators of eutrophic problems in estuaries (see sidebar).

### *What causes hypoxia, anoxia, and eutrophication?*

Hypoxia and anoxia are symptoms of eutrophication, a process in which the addition of nutrients to water bodies, primarily nitrogen and phosphorus, stimulates algal growth. While estuaries have always received nutrients from natural sources in the watershed and from the ocean, in recent decades population growth and related activities such as various agricultural practices, waste water treatment, urban runoff, and burning of fossil fuels have increased nutrient inputs by many times the levels that occur naturally. While low dissolved oxygen conditions may have occurred naturally in some waterbodies, the occurrence, duration, and level of depletion has increased with the recent increases in nutrient inputs. It is important to note that there is no direct link between nutrient inputs and hypoxia. Instead, there is a progression of water quality responses that occur once nutrients reach estuarine waters (Fig. 1).

It is clear that the most important cause of eutrophic conditions is nutrients. However, the progression and expression of symptoms related to nutrient enrichment involves not only nutrients but also the physical properties of the estuary which can enhance or suppress the development of problem conditions. Because the physical properties of estuaries vary widely, the scale and intensity of impacts from nutrients varies widely among waterbodies, and the level of nutrient input required to produce these symptoms also varies.

### *What impairments are caused by eutrophic symptoms?*

Hypoxia and other eutrophic symptoms have a variety of impacts which are shown in Figure 1. Excessive algal growth is a direct response to nutrient additions, which may lead to other, more serious, symptoms such as depleted dissolved oxygen. Dense algal blooms occur in some estuaries for months at a time, blocking sunlight to submerged aquatic vegetation (SAV) which in turn limits SAV growth. Decaying algae depletes dissolved oxygen that was once available to fish, shellfish, and other bottom dwelling organisms. Together with the loss of submerged aquatic

### **Common Eutrophication Symptoms**

#### **Primary Symptoms:**

**Chlorophyll a** is a measure used to indicate the amount of microscopic algae, called phytoplankton, growing in a water body. High concentrations are indicative of problems related to the over production of algae.

**Epiphytes** refer to algae which grow on surfaces of plants or other objects. They can cause losses of submerged aquatic vegetation by encrusting leaf surfaces and thereby reducing light to the plant leaves.

**Macroalgae** are large algae, commonly referred to as "sea weed." Blooms can cause losses of submerged aquatic vegetation by blocking sun light. Additionally, blooms may also smother immobile shellfish, corals, or other habitat. The unsightly nature of some blooms may impact tourism due to declining value of swimming, fishing, and boating opportunities.

#### **Secondary Symptoms:**

**Low dissolved oxygen, including anoxia and hypoxia**, may occur as a result of large blooms of algae that sink to the bottom and use oxygen during the process of decay, or respiration. Low dissolved oxygen can cause fish kills, habitat loss, and degraded aesthetic values, resulting in loss of tourism.

**Loss of submerged aquatic vegetation** occurs when light is decreased by poor water clarity associated with over growth of algae or as a result of epiphyte growth on leaves. Losses of these grasses can have negative impacts on some fisheries because the grass beds serve as important habitat.

**Nuisance and toxic algal bloom** problems are thought to be caused by a change in the natural mixture of nutrients that occurs with long term increased nutrient inputs. These blooms may release toxins which cause fish and shellfish kills. There are also human health problems related to consumption of fish and shellfish that have accumulated algal toxins, and from toxins that become airborne and are inhaled. It is important to note that some toxic algal blooms are naturally occurring.

plants, low dissolved oxygen leads to loss of habitat for fish and other commercially and ecologically important organisms.

Other less obvious impacts include changes in the phytoplankton community structure as a result of changes in nutrient ratios. These changes favor blooms of algae that are less desirable to fish and they may also be toxic to fish and harmful to humans. Serious illness and even death may result from consumption of fish and shellfish contaminated with algal toxins or from direct exposure to water or airborne toxins during blooms. Excessive algal blooms may impact

boating, swimming, and tourism due to declining aesthetic values, in addition to human health concerns. The costs associated with these types of blooms can be considerable, especially if toxic blooms occur at the height of the tourist season.

based on the conditions at present, data gaps, and research needs.

### *What can be done about hypoxia and other eutrophic symptoms?*

Scientists have worked to understand and document the complex issues associated with estuarine eutrophication for nearly 40 years. Study results show a strong relationship among population density and human activities, nutrient inputs, and eutrophic symptoms. In some well studied estuaries, efforts have been made to reduce nutrient inputs with good results (see sidebar on page 17). However, many waterbodies have not been well studied, making management decisions difficult, and in some cases even the condition within the estuary is not well known. What is agreed upon by many experts is that these symptoms can be expected to worsen in the future as coastal populations and nutrient loads increase, unless something is done now to counterbalance that trend. In addition to reducing nutrient sources, further research and monitoring is needed to better understand this complex issue.

### *About this report*

The intent of this report is to provide the state of our knowledge to date about the ecological and economic consequences of hypoxia and other nutrient related water quality problems, alternatives for reducing mitigating and controlling these problems and the social and economic costs and benefits of such alternatives in US coastal waters. There is now a comprehensive picture of eutrophication, and the factors influencing the development of these problems in US estuaries, based on a national assessment involving nearly 400 scientists from academia, Federal and state agencies (Bricker et al. 1999). Information regarding trends and estuarine impairments is less well known, but still based on the comprehensive national assessment. The state of our knowledge of alternatives for reducing mitigating and controlling problems is well developed, but the costs and benefits of the alternatives is less comprehensive, drawing from a limited number of studies that have been done to date.

The current state of our knowledge regarding each of these topics is discussed in this report. In addition, recommendations are made for plausible next steps toward solving these problems,

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# Status and Trends

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*An evaluation was made of the status and trends of hypoxia and other eutrophication related water quality problems in 138 US estuaries and the Mississippi/Atchafalaya River Plume using information acquired from academic, state, local, and federal scientists investigating this problem in these estuaries. The challenge was to use the information for several symptoms to make an assessment of the overall condition within the estuary. The symptoms combined for this assessment, three indicative of the beginning of problems and three indicating more extensive problems, are noted in the model in Figure 1.*

## *Symptoms: Common Signs of Eutrophication.*

The immediate response to increased water column nutrient concentrations is overgrowth of algae, which may be indicated by high levels of chlorophyll a, epiphytes, or macroalgae (see sidebar on page 2 for definitions). It is thought that once primary symptoms are observed at high levels, the estuary is in the first stages of eutrophication.

High expression of chlorophyll a occurs in 39 of the 139 estuaries studied, high expression of macroalgal abundance problems occur in 24, and high epiphyte abundance problems are observed in 11 estuaries. Overall, at least one of these symptoms is observed at high levels in 58 estuaries, meaning that 40 percent of the nation's estuaries may be showing the first stages of eutrophication, though in some cases high levels may be natural. On a regional basis, epiphyte problems occur mostly in Gulf of Mexico estuaries, while higher levels of chlorophyll a and macroalgae are observed in estuaries of all regions (Fig. 2.).

While high levels of primary symptoms are strong indicators of the start of eutrophication, secondary symptoms, which include low dissolved oxygen concentrations, losses of submerged aquatic vegetation, and occurrences of nuisance and toxic blooms, are indicative of more serious problems, even at moderate levels (for a comprehensive assessment of Harmful Algal Blooms in the nation's coastal waters see the companion report available at....). Note that while there is a causative link between nutrients and these symptoms, there are many other factors, both natural and human related, which may contribute to the occurrence of the secondary symptoms.

Depleted dissolved oxygen is expressed at moderate or high levels in 42 estuaries, there are 27 estuaries with moderate or high levels of submerged aquatic vegetation loss, and 51 estuaries with moderate or high nuisance/toxic bloom problems. Overall, for 82 of the 139 estuaries studied moderate or high levels are observed for at least one of the secondary symptoms, an indication that eutrophication is well developed and potentially causing serious problems in over half of the nation's estuaries. The secondary symptoms are somewhat restricted regionally, with the exception of nuisance and toxic blooms which are observed in

systems along all coasts. Losses of submerged aquatic vegetation are most important in the Gulf and Middle Atlantic regions and low dissolved oxygen conditions are observed mostly in the Gulf of Mexico, Middle and South Atlantic regions (Fig. 1).

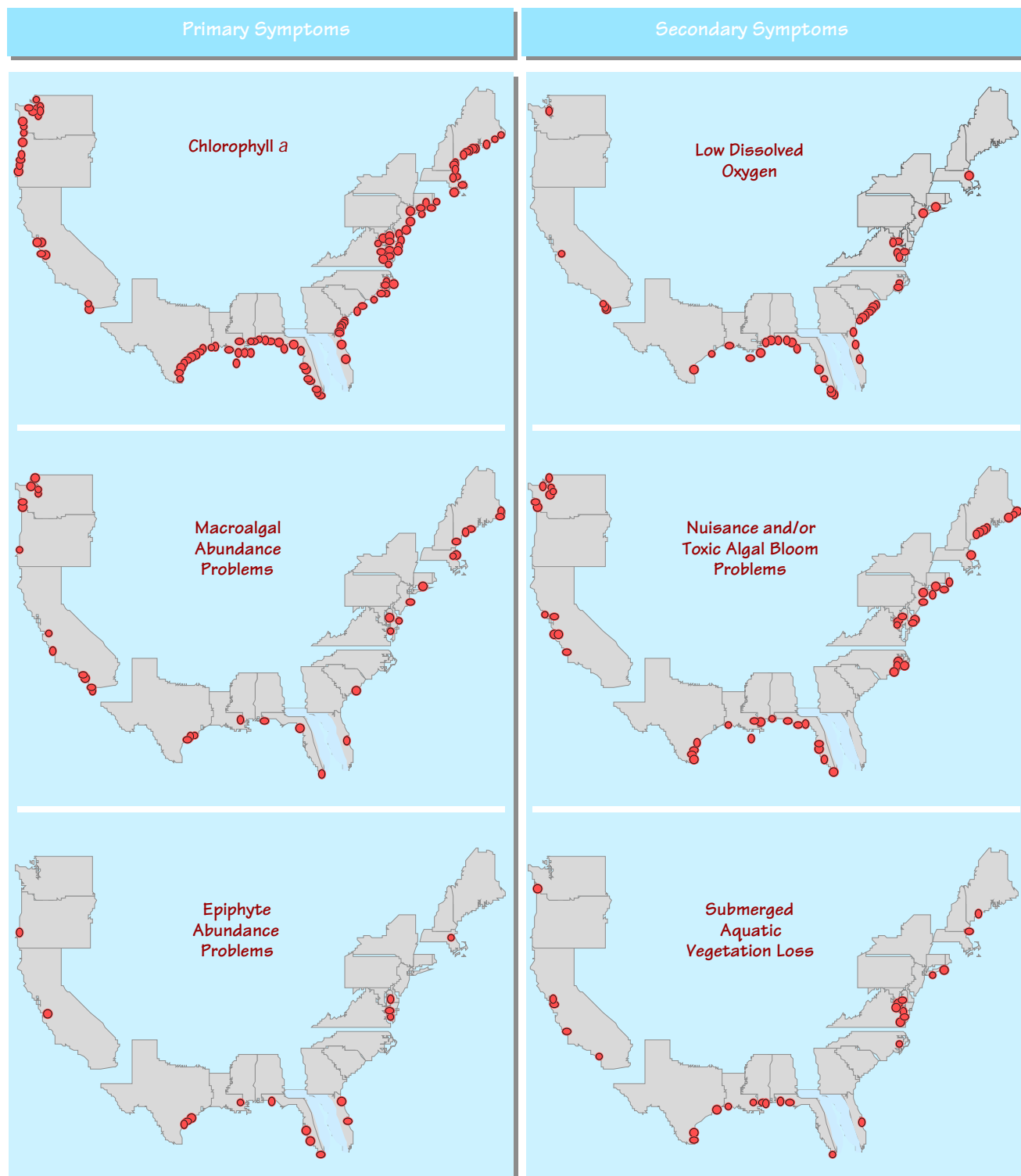
## *Dissolved Oxygen Conditions.*

The low dissolved oxygen conditions shown in Figure 2 represent a combination of information about anoxia (0 mg/l oxygen), hypoxia (>0 but <2 mg/l), and biologically stressful (>2 but <5 mg/l) concentrations. The calculation of expression represents a single value that takes into account the level of oxygen depletion, the spatial area of problem occurrences, and the frequency with which they occur. Figure 3 shows, by region and nationally, the information from which the single value was estimated including the number of estuaries with observed problems (Fig. 3a), the percent of regional area over which the problems occur (Fig. 3b), and the most probable months that they occur (Fig. 3c).

Anoxia is observed at some time during the year in one third of the nation's estuaries, and hypoxia and biologically stressful concentrations are observed in more than half of the nation's estuaries. Biologically stressful concentrations are more extensive than anoxia and hypoxia, observed over greater than one third of the nation's estuarine area. The Gulf of Mexico region has the greatest number of estuaries and the largest regional estuarine area that is impacted, with biologically stressful dissolved oxygen conditions observed over almost 50 percent of the regional area. The Mid and South Atlantic regions also have large areas that are impacted by biologically stressful levels of dissolved oxygen; 30 - 40 percent of regional area in both regions. The North Atlantic is the only region for which no anoxia occurs and the regional area of impact is less than one percent for both hypoxia and biologically stressful dissolved oxygen conditions. Note that the more extreme conditions occur primarily in the summer months, though biologically stressful concentrations may occur at any time of year in the North Atlantic and Pacific region estuaries.

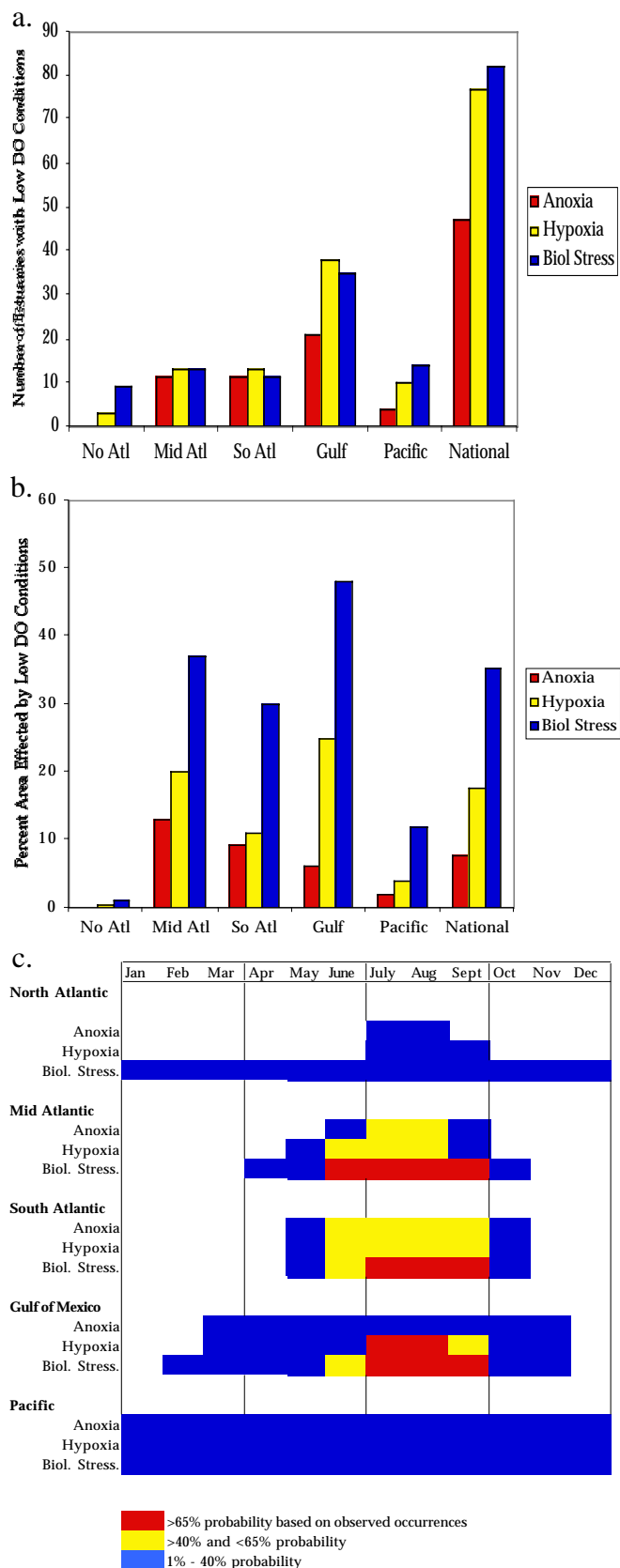
Figure 2. Expression of eutrophic symptoms

The following maps depict estuaries with moderate to high levels of expression of eutrophic symptoms, indicating areas of possible concern. Note that these symptoms are not necessarily related in whole to human-related nutrient inputs; natural causes and other human disturbances may also play a role, to various degrees, in the expression of symptoms.



(from Bricker et al., 1999)

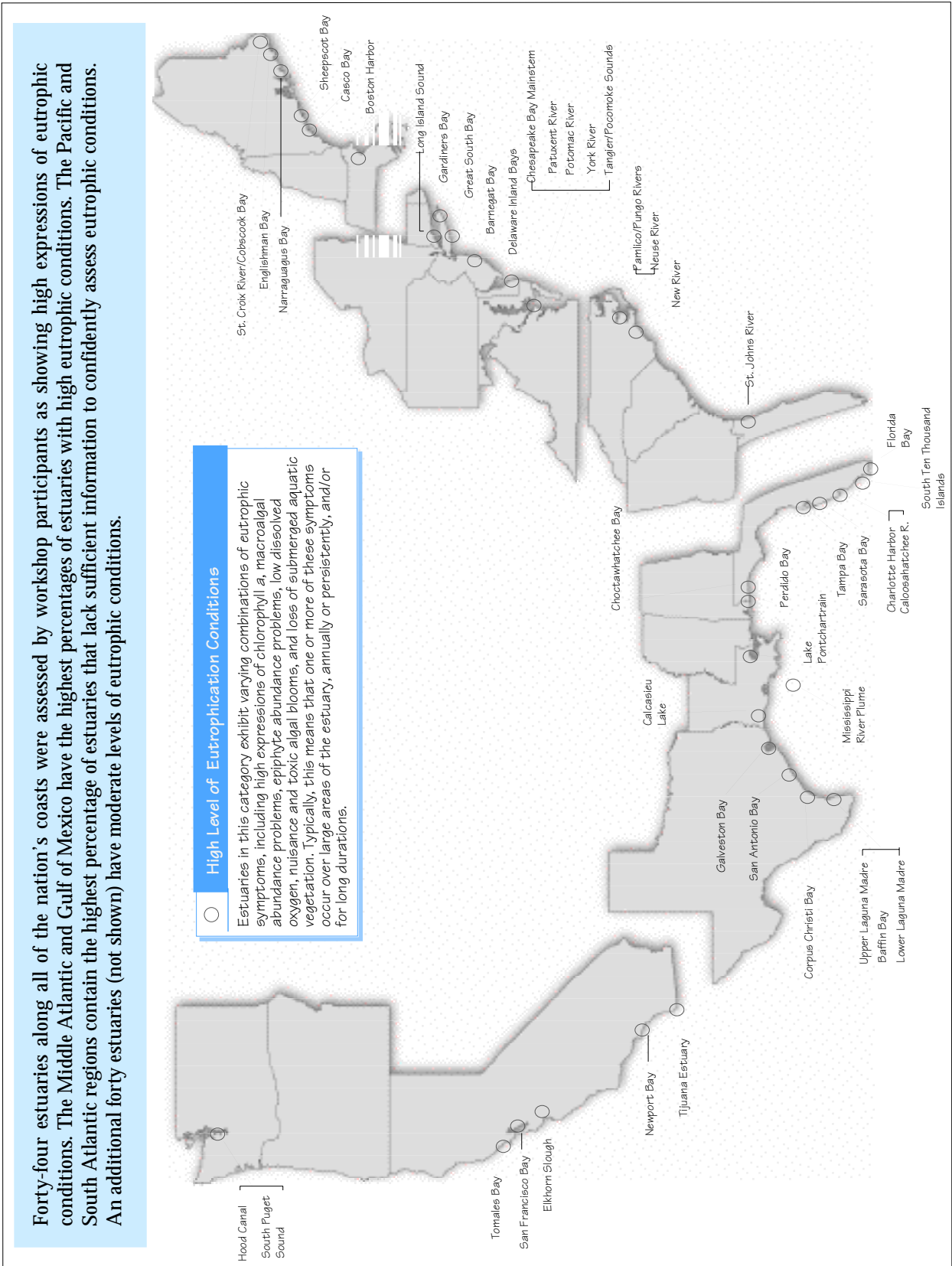
Figure 3a-c. Number of estuaries (a), regional spatial area (b.), and probable months of occurrence (c) of anoxia, hypoxia, and biologically stressful concentrations of dissolved oxygen in US estuaries.



### Overall Conditions.

Combining the primary and secondary symptom conditions provides a picture of the overall conditions within the estuary. High overall levels of eutrophic conditions occur in 44 estuaries (Fig. 4). Although the greatest percentage of estuaries with high level conditions occur in the Gulf of Mexico and Middle Atlantic, there are estuaries along all coastlines that exhibit high overall conditions. This means that one or more symptoms occur at problem levels every year or persistently over a major part of the estuary. An additional 40 estuaries exhibit moderate level eutrophic conditions. This means that substantial problems associated with nutrient enrichment may be occurring in nearly two thirds of the nation's estuaries. The remaining 38 estuaries exhibit low overall levels of eutrophic conditions, meaning that symptoms are not observed at problem levels or that problem conditions occur infrequently or only under specific unusual circumstances. About half of these estuaries are located in the South Atlantic and Pacific regions.

Figure 4. Estuaries with high levels of expression of eutrophic conditions



(from Bricker et al., 1999)

### ***Historic Trends in Eutrophic Symptoms.***

Assessment of symptom trends (ca. 1970 - 1995) is based on data from the eutrophication assessment. The data are less certain than the data for status of conditions and the assessments were less rigorously reviewed. For 51 estuaries, data were insufficient for assessment.

A greater number of estuaries were reported to have worsening conditions for chlorophyll a, epiphytes and macroalgae, nuisance and toxic blooms, and losses of submerged aquatic vegetation than the number of estuaries for which conditions reportedly improved. For dissolved oxygen, there were more estuaries for which conditions showed improvement than worsened. Overall, conditions have worsened in 48 estuaries, improved in 14, and for 26 systems there was no trend in overall eutrophic condition since 1970. Most of the estuaries that have improved overall are located in the Gulf of Mexico. The greatest number of estuaries in which conditions worsened are found in the Gulf of Mexico and in the Mid-Atlantic regions (Fig. 5).

Worsening trends have been attributed to a general increase in population density in estuarine watersheds. Some of these estuaries were historically rural, with farming and urban development intensifying concurrently. Notably, recent toxic blooms that have occurred in estuaries in the Middle and South Atlantic regions are thought to be linked to the increase in confined animal operations and release of untreated animal wastes into local water bodies. There have also been successes, with improvements in water quality over time. These trends are attributed to the implementation of reductions mandated by the Clean Water Act that primarily targeted point sources. In addition, there are National Estuary Programs in some estuaries such as Tampa and Sarasota Bays which are good examples of successful implementation of a “nitrogen diet” that reversed eutrophic conditions (see sidebar on page 17.)

Figure 5 . Trends (1970 - ~1995) in Chl a, Anoxia and SAV by Estuary

	Chlorophyll a (µg/l)	Anoxia (frequency)	SAV (spatial coverage)		Chlorophyll a (µg/l)	Anoxia (frequency)	SAV (spatial coverage)		Chlorophyll a (µg/l)	Anoxia (frequency)	SAV (spatial coverage)
<b>North Atlantic</b>				<b>South Atlantic (cont.)</b>				<b>Pacific</b>			
St. Croix River/Cobscook Bay	•	•	↑	Stono/ North Edisto Rivers	?	?	•	Tijuana Estuary	?	?	•
Englishman Bay	?	?	?	St. Helena Sound	?	?	?	San Diego Bay	•	?	?
Narraguagus Bay	?	?	?	Broad River	?	?	?	Mission Bay	•	?	•
Blue Hill Bay	•	•	•	Savannah River	?	?	•	Newport Bay	?	?	↓
Penobscot Bay	?	•	?	Ossabaw Sound	•	?	?	San Pedro Bay	↓	↓	•
Muscongus Bay	•	?	?	St. Catherine/Sapelo Sounds	?	?	•	Alamitos Bay	?	•	•*
Damariscotta River	•	•	•	Altamaha River	?	?	•	Anaheim Bay	?	?	?
Sheepscot Bay	•	•	?	St. Andrew/St. Simon Sds.	?	?	•	Santa Monica Bay	?	?	•
Kennebec/Androscoggin Rivers	?	?	•*	St. Marys/Cumberland Sds.	?	?	•	Morro Bay	?	?	↓
Casco Bay	•	↓	↓	St. Johns River	•	•	↓	Monterey Bay	•	•	•
Saco Bay	•	?	?	Indian River	↑*	•	↓	Elkhorn Slough	↑	↓	↑
Great Bay	↑	•	↑	Biscayne Bay	•	•	↑	San Francisco Bay	•	•	↓
Hampton Harbor	?	?	↑	<b>Gulf of Mexico</b>				Central San Francisco Bay	↓	•	•
Merrimack River	?	?	↓	Florida Bay	↑	?	•	Drakes Estero	?	?	?
Plum Island Sound	•	•	•	S Ten Thousand Islands	?	•	?	Tomales Bay	?	?	•
Massachusetts Bay	•	•	↓	N Ten Thousand Islands	•	?	?	Eel River	•	?	•
Boston Harbor	•	•	↓	Rookery Bay	•	?	•	Humboldt Bay	•	?	•
Cape Cod Bay	•	•	?	Charlotte Harbor	•	•*	•	Klamath River	•	?	•
<b>Mid-Atlantic</b>				Caloosahatchee River	?	?	↓	Rogue River	?	?	↓
Buzzards Bay	↑*	?	↓	Sarasota Bay	↓	?	↑	Coquille River	?	•	•
Narragansett Bay	•	?	•	Tampa Bay	↓	↓	↑	Coos Bay	?	•	•
Gardiners Bay	•	?	↑	Suwannee River	•*	?	•*	Umpqua River	?	•	?
Long Island Sound	•	↑	↓	Apalachee Bay	↓	↓	↑	Suislaw River	?	?	•
Connecticut River	?	?	?	Apalachicola Bay	•	•	•	Alsea River	?	•	•
Great South Bay	•	?	↓	St. Andrew Bay	↑	?	?	Yaquina Bay	•	•	•
Hudson R./Raritan Bay	•*	?	↓	Choctawhatchee Bay	•	?	↓*	Siletz Bay	?	•	?
Barnegat Bay	•	?	?	Pensacola Bay	↑*	?	↓	Netarts Bay	?	•	•
NJ Inland Bays	↑*	?	?	Perdido Bay	•	?	•*	Tillamook Bay	?	•	•
Delaware Bay	•	?	•	Mobile Bay	?	?	•	Nehalem River	?	•	•
DE Inland Bays	•	?	•	Mississippi Sound	↓	?	↓	Columbia River	•	?	•
MD Inland Bays	•	?	?	Lake Borgne	?	?	?	Willapa Bay	•	?	↓*
Chincoteague Bay	?	?	↑	Lake Pontchartrain	•	•	↓	Grays Harbor	?	?	?
Chesapeake Bay	•	•	↑	Breton/Chandeleur Sounds	?	?	↓	Puget Sound	•	?	↓
Patuxent River	•	•	•	Mississippi River	•	•	•	Port Orchard	?	?	↓*
Potomac River	↓	•	↑	Miss./Atchaf. River Plume	↑	?	•	South Puget Sound	?	?	?
Rappahannock River	↑	?	↑	Barataria Bay	↑	?	↑	Hood Canal	?	?	?
York River	↑	?	•	Terrebonne/Timbalier Bays	↑	?	↑	Skagit Bay/Whidbey Basin	•	?	?
James River	↑	?	↑	Atchafalaya/Vermilion Bays	↑*	↑	?	Washington Coastal Bays	?	?	↑
Chester River	•	•	↑	Atchaf./Miss. River Plume	↑	?	•				
Choptank River	•	↑	↑	Mermentau Estuary	?	•	•				
Tangier/Pocomoke Sounds	↑	•	↑	Calcasieu Lake	↑	•	↓				
<b>South Atlantic</b>				Sabine Lake	•	•	•				
Albemarle/Pamlico Sounds	?	?	↓	Galveston Bay	•	↓	↓				
Pamlico/Pungo Rivers	↑	•	↓	Brazos River	•	•	•				
Neuse River	↑	↑	↓	Matagorda Bay	•	•	↑				
Bogue Sound	•	•	?	San Antonio Bay	•	?	↓				
New River	?	?	?	Aransas Bay	•	•	?				
Cape Fear River	?	?	?	Corpus Christi Bay	↑	•	•				
Winyah Bay	?	?	?	Upper Laguna Madre	↑	•	↓				
N/S Santee Rivers	?	?	?	Baffin Bay	↑	-	↑				

Key:

- \* = speculative
- ? = unknown
- = no trend
- ↑ = increasing
- ↓ = decreasing

Note: Trends shown here represent the largest salinity zone in the estuary (for most estuaries this is the mixing zone). They do not represent conditions throughout the entire estuary.

# Influencing Factors

*There is now a comprehensive picture of the conditions of hypoxia and other nutrient related symptoms in US estuaries from which a plan can be developed for remediation and management. However, for these plans to be successful, it is also necessary to understand the factors influencing the development of these problems. An evaluation of sources of nutrients was made and compared to the conditions within the estuary to try to develop some cause effect linkages that could be used to target management actions.*

## **Nutrient Inputs and Susceptibility.**

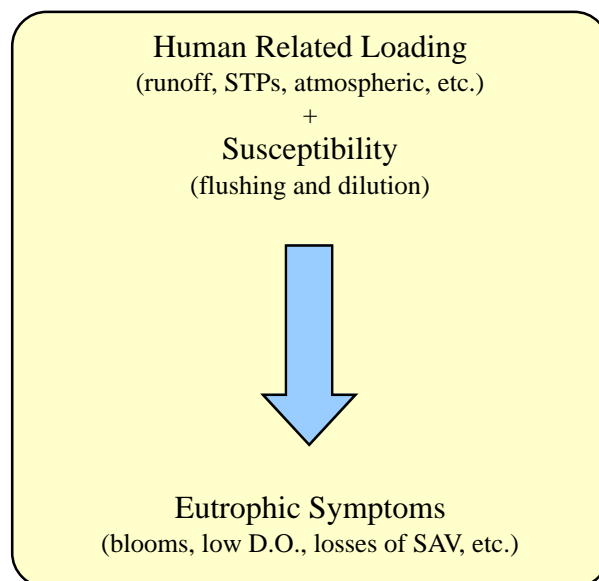
The level of increase of nutrient loadings to estuaries, above those which are natural, is a critical factor determining the level to which they will develop symptoms. Excess nutrient inputs are mostly human related, due to high coastal population density, various agricultural practices such as fertilizer applications and animal feed lot operations, as well as burning of fossil fuels, and sewage treatment effluents. However, the level of water quality response also depends upon the natural physical processes within estuarine waters.

In addition to nutrient inputs, estimates were made of the natural tendency, or susceptibility, of an estuary to retain or export nutrients. How fast water moves through the estuary is determined by tidal action and the amount of freshwater flowing in from rivers. In general, if the water (and nutrients) are flushed quickly, there is not sufficient time for problems to develop and the estuary is not particularly susceptible. If the estuary acts more like a bathtub, with water sitting for a long time, then there is time for nutrients to be taken up by algae. These estuaries are more susceptible to development of eutrophic problems (see sidebar on susceptibility on page 11).

## **Natural and Human Related Influencing Factors.**

In an effort to determine the influence of human and natural factors on the development of eutrophic conditions, the overall eutrophic condition was considered with respect to the nutrient inputs and susceptibility. Nitrogen input values were the primary source of information used for the evaluation of the influence of human sources. Population density and land use was used to try to account for phosphorus and to corroborate the nitrogen estimates. The susceptibility values used were a combination of the flushing and dilution times (see sidebar page 11).

Many estuaries assessed as having high levels of overall eutrophic conditions also have high



susceptibility and moderate to high levels of nutrient inputs. The converse also seems to hold true, that estuaries with low susceptibility and low inputs of nutrients have low overall level of eutrophic conditions. In fact, of the 44 estuaries with a high level of eutrophic condition, 36 were assessed as having a high level of human influence on development of conditions. These estuaries have moderate to high levels of nutrient inputs but they also have moderate to high susceptibility. In these systems the natural system characteristic enhance the expression of symptoms. One implication is that since the symptoms are influenced significantly by human related inputs, there is a good chance that reductions in these inputs will result in reductions in symptoms. Most of these estuaries are found in the Gulf, Mid-Atlantic and Pacific regions.

In contrast, there are 21 estuaries that exhibit low overall eutrophic conditions and low anthropogenic influence. The common traits of these estuaries is lower susceptibility and lower nitrogen inputs. In these systems, the natural characteristics appear to suppress the expression of symptoms. Most of these estuaries are located in the South Atlantic region.

It is important to note that although these generalizations can be made, there is not a completely predictable relationship between inputs and the

## A Classification of Physical Transport Processes and the Susceptibility to Nutrient-Related Water Quality Impacts in 138 US Estuaries

Are some estuaries naturally more susceptible to nutrient-related impacts?

Estuaries can be classified based on physical transport processes that, in part, determine their susceptibility to nutrient-related water quality conditions. A susceptibility index (the Estuarine Export Potential, EXP) was developed using physical and hydrologic data, assembled by NOAA's National Ocean Service, for 138 estuaries in the conterminous US.

**Physical Processes that Determine Susceptibility.** The EXP proposes that an estuary's susceptibility to nutrient-related water quality concerns is determined by two key physical factors -- the dilution capacity of the water column and its flushing/retention time (Figure 1). Dilution capacity is determined by the volume of water available to concentrate nutrient supplies. In vertically homogenous estuaries, the dilution volume is equal to the estuary volume. In contrast, for vertically stratified systems, the dilution volume is limited to the upper layer of the water column (above the pycnocline). Flushing is the time required for freshwater inflow and tidal prism volume (modified by a re-entrainment coefficient) to replace the estuary volume. The index, which represents average annual and system-wide conditions, provides order-of-magnitude separation for the 138 estuaries.

Intuitively, the results suggest that estuaries with larger dilution volumes and faster flushing times are comparatively less susceptible to nutrient-related water quality symptoms. Perhaps more revealing, is the apparent grouping (or "classification") of estuaries with respect to susceptibility (i.e., a similar EXP).

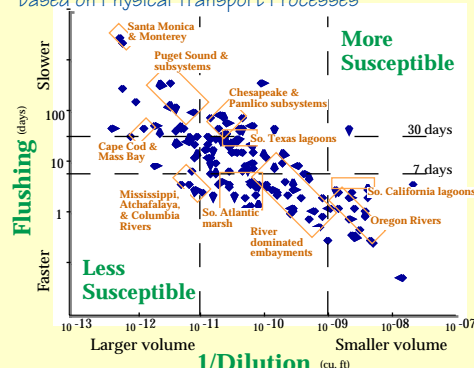
**Applying the EXP.** One way to apply the susceptibility concept is to couple the EXP with nutrient load estimates from each estuarine watershed (Figure 2). This provides an inferred nutrient concentration in the water column (mg/l) which suggests, in a comparative sense, the potential for nutrient-related water quality symptoms. For example, higher nutrient concentrations imply the potential for more extreme expressions of nutrient-related symptoms. The validity of this application is being evaluated against a recent NOS study, the National Estuarine Eutrophication Assessment, that characterizes the scale and severity of water column nutrient concentrations and other nutrient-related symptoms for all 138 estuaries.

This approach also has the potential to suggest how responsive the system may be to additional nutrient loads or nutrient abatement strategies. For example, estuaries in the upper left portion of Figure 2 would have to add or reduce comparatively more nutrients to affect water column concentrations than estuaries in the lower right. Likewise, this work may begin to describe how changes to an estuary's physical environment could potentially alter its susceptibility to nutrient-related conditions. For example, the dilution or flushing components of EXP could be affected by alterations in freshwater inflow (e.g., diversions, impoundments, or consumptive loss) or tidal exchange (e.g., inlet modification, channel dredging).

**EXP Validation and Refinement.** The model's methods and results are currently being reviewed by subject experts, while NOS pursues more rigorous coupling of EXP with National Estuarine Eutrophication Assessment results. At the same time, NOS has initiated refinements to the model that will help increase both spatial and temporal resolutions. This will enable NOS to evaluate the relative susceptibility of various regions within estuaries during a range of runoff conditions.

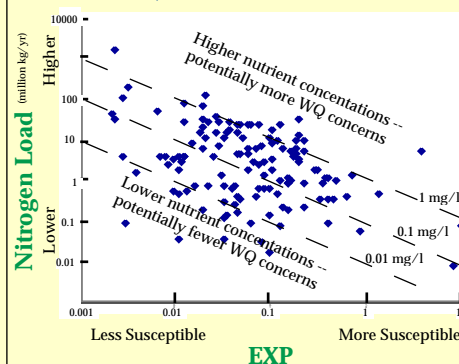
$$\text{EXP} = \frac{\text{unit nutrient load (mass/volume)}}{\text{1/dilution volume of estuary (1/volume)}} \times \text{flushing time (time)}$$

Figure 1. Determining the EXP - Classifying Estuaries based on Physical Transport Processes



Names were assigned only as general descriptors of estuaries in these groups and are not intended to be consistent with geomorphologic classifications.

Figure 2. Predicting the Potential for Nutrient-Related WQ Impacts



Nitrogen load estimates adapted from USGS SPARROW model

expression of symptoms, or between the susceptibility and expression of symptoms. There are exceptions to these general rules, including six estuaries assessed with a high level of eutrophic condition and low human influence. Five of these are located in the North Atlantic region where the susceptibility is low due to tidal ranges greater than six feet, and nitrogen inputs are low due to low population density and a mostly forested watershed. The overall eutrophic condition is assessed as high because nuisance/toxic blooms occur each year, however, these are natural, originating outside and then drifting into the estuary.

### ***Nutrient Sources***

Using data only for the group of 44 estuaries with high level expression of eutrophic conditions, an analysis was performed to try to identify the major nitrogen sources. Of these 44 estuaries, non-point sources account for greater than 75 percent of total nitrogen input for 32 estuaries. Point sources accounted for greater than 75 percent of total input for only 1 of these estuaries (Boston Harbor).

A further analysis was performed to identify the dominant component of the non-point sources among atmospheric, fertilizer, livestock, and urban contributions. For 17 of the 44 estuaries with high level of expression of eutrophic conditions, agricultural sources accounted for greater than 50 percent of non-point inputs. Urban sources accounted for greater than 50 percent of the non-point source contribution for 7 of these 44 estuaries. This is consistent with the 305(b) reporting by states summarized in the Clean Water Action plan, that the leading cause of water quality impairments is polluted runoff. Further, they report that agriculture is the most extensive source, affecting 70 percent of impaired rivers and streams.

# — Environmental and Ecological Impacts —

*There are many estuarine impairments that are attributable to hypoxia and other eutrophic conditions. The human use impairments are somewhat easier to evaluate than ecological impairments such as the effects on community trophic structure.*

## **Estuarine Impairments.**

Hypoxia in coastal waters can have a variety of impacts. Effects on the fishery resources can include direct mortality to fish and their food base, as well as indirect effects such as altered migration patterns, reduction in suitable habitats, increased susceptibility to predation, and disruption of spawning and recruitment. Fishing catches in hypoxic areas rapidly decline to zero. The changes in nutrient ratios that can be associated with hypoxia can also lead to ecosystem changes such as shifts in algal and benthic community structure. Research findings indicate that during hypoxic events, changes in ecosystem energy flows favor opportunistic species with shorter life cycles, resulting in an overall reduction in biodiversity.

Other possible impacts associated with hypoxia and the related symptoms of estuarine eutrophication (e.g., algal blooms) include restrictions on swimming and boating, beach closures, loss of tourism because of aesthetic and public health concerns, and restrictions on consumption of fish and shellfish. Human health risks are increased by the occurrences of toxic blooms which can accumulate in fish and shellfish tissue and may cause problems directly if the toxins that become airborne during the time of a bloom are inhaled. This does not address economic losses which at present are not well known (see Costs and Benefits section), however, they may be considerable in estuaries where symptoms occur during the height of the tourist and/or fishing seasons.

The finding that over half of the Nation's estuaries have moderate to high expressions of at least one of the secondary symptoms (low dissolved oxygen, nuisance/toxic blooms, losses of SAV) is of considerable importance because these symptoms negatively impact estuarine resources as described above. Although the magnitude of these impacts cannot currently be quantified, estuarine uses that are known or suspected to be impaired because of eutrophic symptoms were identified. Although this is qualitative information, it is still useful in helping to understand the nature of impaired uses (Table 1). In all, some type of use impairment was identified in 69 of the 139 estuaries studied. Note that the impairments are attributed to eutrophic conditions in general, not just low dissolved oxygen.

The most frequently reported impairments are to commercial fishing and shellfish harvesting. Considered regionally, fishing and/or shell fishing impairments are reported for all coasts. Other frequently reported impairments are aesthetics for the Mid-Atlantic coast, and tourism for the Gulf of Mexico. Loss of assimilative capacity – the ability of an estuary to receive nutrients without exhibiting negative symptoms – also appears to be important, particularly in the South Atlantic region. These results are supported by the 305(b) reporting by states for 1996 showing that of the estuaries surveyed, 38 percent are reported to be partially or fully impaired, with water quality threatened in an additional four percent.

*Table 1. Number of estuaries with impaired resource uses attributable to eutrophic symptoms.*

Region	Number of Estuaries With Impaired Uses	Commercial /Recreational Fishing	Fish Consumption	Shellfish	Swimming	Boating	Aesthetics	Tourism
North Atlantic	12	0	0	11	0	1	0	0
Middle Atlantic	16	12	0	9	6	2	8	2
South Atlantic	9	8	3	3	1	1	0	2
Gulf of Mexico	19	11	5	12	4	1	4	10
Pacific	13	12	0	11	4	0	5	0
<b>National</b>	<b>69</b>	<b>43</b>	<b>8</b>	<b>46</b>	<b>15</b>	<b>5</b>	<b>17</b>	<b>14</b>

# Strategies to Reduce, Mitigate, Control Hypoxia and Costs and Benefits of Alternatives

*There are a variety of methods that can be used to reduce nutrient inputs to waterbodies with the intent of reducing the occurrence of hypoxia and other nutrient related water quality problems in US coastal waters. The following describes a cross section of the methods that can be applied and a discussion of estimated costs and benefits of these alternatives. Descriptions of the Federal and state laws that provide oversight for implementation of alternatives can be found in Appendix 1.*

## Strategies for Reducing Nutrient Inputs

The primary cause of the excessive algal growth (and the subsequent die-off, bacterial decomposition, and oxygen depletion) that leads to hypoxic and anoxic conditions in coastal waters is an over abundance of the plant nutrients nitrogen and phosphorus in the water column. Because nitrogen is generally considered the nutrient that limits

algal growth rate in estuarine and marine systems, reducing the extent and severity of hypoxia requires that nitrogen inputs to coastal waters be controlled.

There are two general approaches for reducing nutrient inputs: controlling inputs at the source; and intercepting and sequestering or transforming nutrients once they are being transported through the watershed. Within these two categories are a variety of potential methods that can be implemented (Table 2).

A prerequisite for determining the most effective strategy(ies) is an understanding of the relative contribution of nitrogen from the major sources within a watershed, which depends on the mix of landuses, soil types, and human activities in the watershed. Table 3 shows estimates of different source contributions from several watershed assessments. Note the variation in the relative importance of sources among watersheds. For example, in the Mississippi River Basin, nonurban nonpoint sources dominate, followed by atmospheric inputs, whereas in a more urbanized basin such as the Narragansett Bay watershed, urban and point sources are the most significant sources.

Resource managers and policy makers must take into account the relative contributions among sources in designing the optimum mix of nutrient control strategies for a watershed. Further, because there is no single best method or data source for estimating the relative contribution of nutrient sources within a watershed, it is important to use estimates from several independent approaches in determining the relative contributions.

This approach was followed in Tampa and Sarasota Bays and reductions in nitrogen discharge were implemented. While there was about a five year lag between the reductions and measurable response in water quality indicators, the success in these systems should be taken as an encouraging sign that nutrient controls do work, given appropriate time and resources (see sidebar on page 17).

Table 2. Possible Methods for Controlling Nitrogen Inputs

Non-Point Source Controls	
Agriculture: On-Site	
	Change Cropping Systems
	Reduce Fertilizer Application Rates
	Manage Manure Spreading
	Manage Time of Fertilizer Application
	Use Nitrification Inhibitors
	Change Tillage Methods
	Increase Drainage Tile Spacing
Off Site	
	Wetlands
	Riparian Zones
	Controlled Drainage
Silviculture	
	Source reductions during de- and re-forestation
Urban Runoff	
	Stormwater Runoff
	On-Site Sewage Disposal
	Source Reduction (reduce pet waste and lawn fertilizer, sweep streets)
Point Source Control	
	Municipal Wastewater and Feedlot Wastewater
	Environmental Technology
	Ecotechnology
Control of Atmospheric NOx	
	Stationary Source Control
	Mobile Source Control
Control Flooding/Diversions	

Table 3. Relative Contributions of Total Nitrogen to Estuarine Waters (percent)

Nitrogen Sources	Watershed			
	Mississippi Riv	Tampa Bay*	Chesapeake Bay	Narragansett Bay*
Nonurban Nonpoint	65	30	57	negligible
Urban Nonpoint	negligible	15	9	6
Point Source	11	14	23	89 (includes river + upstream)
Atmospheric	24	29	11	5

\*Note that an additional 12 percent of loading to Tampa Bay enters through groundwater/springs and via dockside fertilizer losses. Rivers and upstream sources including both nonpoint and point sources, account for 61 percent of input to Narragansett Bay. Since much of the nitrogen has been added by upstream sewage treatment plants, these sources are considered point sources for this exercise.

### Specific Methods for Reducing Nitrogen Inputs

The operational implementation of some nitrogen reducing methods, their effectiveness, and some cost considerations are described below.

#### Changing Cropping Systems and Tillage Methods

Modifying or changing cropping systems can reduce inputs and runoff of agricultural chemicals that contribute nutrients to surface and groundwater. Examples include establishing and maintaining perennial vegetative cover, changing cropping sequence, implementing conservation tillage and contour farming. These systems range in effectiveness for removal of nitrogen from approximately 20% for terrace systems to 70% for filter strips. Effectiveness of individual practices can vary widely depending on site-specific conditions. Costs in 1985 on a national average range from approximately \$90 per acre for terraces to \$48 per acre for permanent vegetative cover. Costs for a typical mid-Atlantic state (Maryland) for conservation tillage averaged \$18 dollars per acre in 1987.

#### Reducing Fertilizer Application Rates through Nutrient Management

Nutrient management reduces nutrient inputs to fields by developing nutrient budgets for crops, applying nutrients at times where they are most subject to uptake by crops, applying only the types and amounts necessary for a particular crop, and considering site conditions in terms of vulnerability. Nutrient management can include use of soil surveys to determine soil productivity and identify environmentally sensitive sites, using past history to determine realistic crop yield expectations, soil testing, plant tissue testing, manure, sludge, mortality compost, and effluent testing,

use of proper timing, formulation, and application methods, and use of cover crops to scavenge nutrients remaining in the soil after harvest. Effectiveness of nutrient management varies, but USDA reports that improved nutrient management has resulted in nitrogen application reductions of 33.1 pounds/acre treated for surface water protection, 28.4 pounds/acre treated for ground water protection, and 62.1 pounds of phosphorus per acre treated for water quality protection in its 16 Water Quality Demonstration Projects and 74 Hydrologic Unit Areas (USDA, 1992). Costs associated with nutrient management are largely associated with the technical assistance needs and other consulting services to develop nutrient management plans. In many cases, farmers actually save money as a result of lower fertilizer application rates and reduced costs for commercial fertilizer.

#### Managing Animal Waste to Reduce Runoff

Improving the management of animal waste (manure) from facilities that produce livestock can reduce associated nutrients and runoff from areas where animals are concentrated. Practices for animal waste management include dikes and diversions to prevent flow of runoff directly into receiving waters, grassed waterways that reduce erosion and include vegetation that can serve to uptake some nutrients, and roof runoff and other water management systems to keep clean water from coming in contact with animal waste. In addition, animal waste storage structures and proper utilization of animal waste through land application or removal are important as a means to contain and control related pollutants. Animal waste systems, including methods for collecting, storing, and disposing of runoff and process generated wastewater, can achieve a gross effectiveness of 80% for reduction of nitrogen, though site-specific conditions can vary widely and

influence effectiveness. Construction costs (in 1990 dollars) for sample elements of a waste management system include diversions at \$2 per foot, retention ponds (depending on size) ranging from \$.31 to \$2.58 per cubic foot, and settling basins (depending on size) ranging from \$1.08 to \$4.26 per cubic foot.

#### *Wetlands, Riparian Buffers, and Controlled Drainage to Filter Nutrient Pollution*

Constructed wetlands, riparian buffers, and other drainage structures can reduce nutrients through filtration, deposition, infiltration, and absorption. These systems can be strategically placed adjacent to waterbodies to intercept nutrient runoff before it enters lakes, streams, rivers and estuaries. Research by Dillaha et al., indicates effectiveness of vegetated filter strips for total nitrogen removal in the range of 50% - 90%, depending on length of the strip. Nitrogen removal from constructed wetlands varies widely from 10% to 76%. Costs for these systems vary widely, depending on the width of the buffers, whether new vegetation is being established, and the extent of area and volume of runoff that will be treated. Assuming an average filter strip of 66 feet in width, the associated costs are \$85.41 per acre in 1990 dollars and the average constructed wetland project cost approximately \$20,000 in 1992.

#### *Reducing Nutrients from Forestlands*

Though intact forest systems provide one of the most valuable land uses for protecting water quality, forest harvesting and disturbance can release nitrogen and contribute to downstream water quality problems. Proper forest harvesting techniques, chemical management, and site preparation and regeneration of new tree stock are important practices for ensuring that silviculture does not cause nutrient pollution. Leaving the forest floor litter layer intact during site preparation (as opposed to mechanical preparation) maintains infiltration and slows runoff. Total nitrogen losses are nearly 20 times greater from sheared than from undisturbed watersheds, with nitrate losses of .227 kg/hectare for sheared and windrowed tracts as opposed to .001 kg/hectare for undisturbed land. Although fertilizers are rarely used in tree planting, proper nutrient management remains important for forested lands, particularly where sewage sludge is applied. Costs are generally less for less intensive site preparation, but the important comparison is the yield for a given investment. The cost-benefit ratio for light site preparation provides a 2.3

percent greater internal rate of return than that for heavier site preparation.

#### *Reducing and Controlling Urban Runoff*

Stormwater from rooftops, parking lots and city streets contributes slugs of nitrogen to local waterways during heavy rainfall events. Structural practices can be applied to reduce urban runoff volumes and velocities, thereby providing controls that can be used to treat runoff through infiltration, filtration and detention. Infiltration practices rely on adsorption of runoff by soil particles or other media which allow water to seep into the ground and have nutrients removed by biological action. Filtration practices include grassed swales and filter strips that slow runoff velocity and allow settling of pollutants, including some uptake by the vegetation. Detention practices can include ponds or other structures that store runoff volumes. Removal efficiencies for structural practices vary widely, averaging 35% for total nitrogen from a sand filter/filtration basin to 55% for an extended detention wet pond. However the range of efficiencies for a given practice can be even greater, with extend wet detention achieving a probable range anywhere from 10 - 90% for total nitrogen. Construction costs averaged \$5 per cubic foot for a sand filter/infiltration basin and \$.5 per cubic foot of storage volume for an extended detention wet pond in 1991.

#### *Managing On-Site Sewage Disposal Systems*

On-site sewage disposal systems or septic systems can contribute excessive nitrogen to groundwater which feeds into surface water. Ensuring proper installation of new septic systems, properly maintaining existing systems and replacing failing systems can reduce potential for system failure and remedy situations where failing systems are contributing to surface water pollution. Proper installation of new systems largely involves finding a suitable location where conditions are acceptable for subsurface treatment of wastewater effluent. Where conditions are limiting, alternative systems may be necessary. For existing systems, periodic inspection and maintenance (including pumpout, cleaning, etc.) are necessary to keep systems operating properly. Nitrogen removal by on-site sewage disposal systems varies by type. A conventional septic system achieves an average nitrogen removal of 28% where an intermittent sand filter can achieve an average nitrogen removal of 55%. The capital cost for these two systems is approximately \$4,500 per household for the conventional system and \$5,400

## Tampa and Sarasota Bays: Reversing Nitrogen-Driven Eutrophication

Nutrient related water quality degradation is causing losses of seagrass meadows in most parts of the world. However, in Tampa and Sarasota Bays on Florida's southwestern coast, seagrass coverage is increasing. These subtropical estuaries both have highly urbanized watersheds, yet management actions have brought about noticeable improvements during the last decade.

The depth and extent of seagrass beds in these bays are closely associated with nitrogen loadings. Historically (pre 1930s), seagrass meadows are believed to have covered 31,000 ha of the shallow Tampa Bay bottom. However, impacts to the bay from population and industrial development of the Tampa Bay area resulted in increased nitrogen loading, high chlorophyll concentrations, and subsequent large seagrass reductions due to reductions in light penetration. By 1982, approximately 8,800 ha of seagrass remained, a 72% loss from the early estimate.

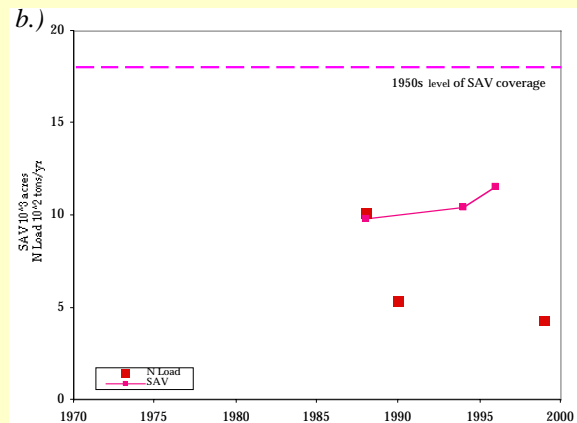
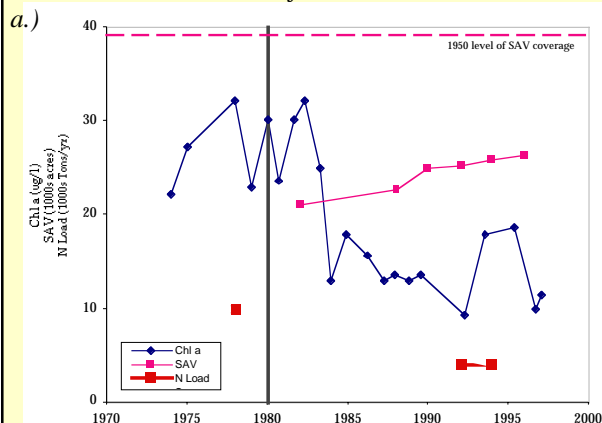
Water quality monitoring programs in Tampa Bay show that chlorophyll concentrations since 1985 have returned to levels observed in 1950, and since 1988, the trend of seagrass loss has been reversed. The bay-wide seagrass coverage in 1996 was estimated at 10,930 ha, a 25% increase since 1982. Seagrass recovery is attributed to a nearly 50% reduction in nitrogen loading from domestic wastewater treatment plants that occurred in the early 1980s which resulted in reductions in phytoplankton biomass and increased light attenuation.

To maintain the improvements, participants in the Tampa Bay National Estuary Program have adopted nitrogen loading targets based on water quality and related light requirements of restoring turtle grass *Thalassia testudinum*. A Nitrogen Management Consortium consisting of a local electric utility, industries and agricultural interests, as well as local governments and regulatory agency representatives, has been established to develop and implement a Consortium Action Plan. To date, implemented and planned projects are expected to reduce existing nitrogen loads by 140 tons/year by the Year 2000, which meets and exceeds the agreed-upon reduction goal.

In Sarasota Bay, a similar management philosophy was established by the Sarasota Bay National Estuary Program and its partners; wastewater treatment was improved, agricultural re-use programs were expanded and a deep well injection site for wet weather disposal of effluent was developed. In response, seagrasses have begun to flourish again, increasing 20% percent from 1988-1998.

Although the complexity of nutrient inputs and related eutrophication problems may seem insurmountable, results from these two estuaries should serve as an optimistic example that eutrophication impacts can be reduced and even reversed in some cases. A strong technical basis for management actions, and commitments to implement those actions has been key to the results observed in Tampa and Sarasota Bays.

Tampa Bay (a) and Sarasota Bay (b) Chl a concentration (Tampa only), SAV spatial coverage, and N loading. a.) Note that Tampa wastewater plants reduced their nitrogen loading by about 90% in 1980 (denoted by grey line). After a 5 year lag, Chl a began to decline and has now reached 1950s levels. At the same time SAV began to increase (approximately 500 acres per year since 1988) but still has not reached 1950s level of coverage. b.) Sarasota Bay nitrogen inputs have declined also and SAV is increasing but has not yet reached 1950s levels. (Greening et al, 1997; Johansson and Greening, in press.; Tomasko and Ries, 1997; Greening and Holland, 1999; Sarasota Bay NEP, 1999)



for the intermittent sand filter, a difference of \$900.

### *Preventing Pollution from Households and Homeowners*

A variety of activities that generate nutrient pollution occur as a result of actions by homeowners and urban residents. In particular, garden and lawn care activities and improper disposal of pet waste can result in significant inputs of nitrogen to area waterways. Proper landscape and turf management are as important for urban lawns as nutrient management is for agricultural lands. Reducing fertilizer use, soil testing and reducing grassy areas through landscape plantings that absorb runoff can reduce nitrogen loadings from urban yards. Efficient watering techniques and also reduce runoff – overwatering can increase nitrogen loss 5 to 11 times the amount lost when proper water strategies are employed. Managing pet excrement to minimize runoff into surface waters is also important, as many nutrient problems in urban streams have been tied to this source. Requirements that pet owners pick up and properly dispose of animal feces is a means to reduce the impact of pet waste on surface water quality.

### *Reducing and Controlling Point Source Inputs*

Municipal wastewater treatment plants are the primary point source discharge of nitrogen to waterways in the United States, though industrial sources are also important in selected basins. Tertiary treatment is needed to achieve significant nutrient removal levels. The two major categories of tertiary treatment are environmental technologies and ecotechnologies, the latter involving wetland treatment systems.

*Environmental technologies* include a wide range of physical, chemical, and biological methods of nutrient reduction. Percent removals range from 40 to over 90 percent, depending on the specific technology. These technologies require a high level of engineering and maintenance to achieve high levels of removal, however, they require little land.

Physical/chemical technologies rely on controlled use of chemical and mechanical energy within concrete or earthen containers. These technologies have proven successful in treatment of wastewater, with the exception of those plants that combine wastewater and storm water; these technologies are most suitable to controlled flow situations. The three commonly used physical/chemical

processes for control of nitrogen in wastewater are air stripping, breakpoint chlorination and ion exchange. These technologies are expensive and labor intensive, however, reduction of nitrogen can be significant with removal rates varying from 20 to over 90 percent.

Biological processes to remove nitrogen from water treatment plants act principally through the activated sludge process. This process relies on microbial action to consume unwanted substances which flocculate and settle, forming sludge that can be removed from the bottom of the container. Removal rates vary from five to over 90 percent.

*Ecotechnologies* rely on the well documented retentive capacity of wetlands, which are used to treat wastewater effluent. Typically, wetlands are constructed for either surface flow over the substrate or sub-surface flow through a substrate and require much more land than the environmental technologies. Removal efficiencies range from 46 to 72 percent, consistent with the engineered technologies. However, the generally lower cost of these wastewater treatment wetlands adds to their desirability as nitrogen control systems.

### *Control of Atmospheric NO<sub>x</sub>*

Atmospheric nitrogen emissions come from two major source categories, stationary (i.e. power plants) and mobile (i.e. cars). Control of both types of sources involves facilitating complete combustion so that poisonous nitrogen oxide gases (NO<sub>x</sub>) that are released in less efficient combustion processes, are transformed into inert nitrogen gas (N<sub>2</sub>).

Stationary source reductions involve control during combustion or post-combustion processes. In the first, the combustion process is modified to control the coal-air mixture or to reburn flue gases, and can reduce nitrogen oxide emissions by 35 to 72 percent. The post combustion processes involve injecting flue gas with a catalyst and can reduce nitrogen oxide emissions by 35 - 90 percent.

Mobile source controls are implemented via base engine emissions, air-fuel ratio control, better fuel delivery and atomization and treatment of exhaust. Engine improvements increase the engine thermal efficiency and thus the combustion process, and result in lower nitrogen oxide emissions by as much as 35 percent. Control of the fuel-to-air ratio is designed to maximize engine

**Table 4: Nationwide Estimates of Capital Costs for Nonpoint Source Pollution Controls (Billions of 1996 Dollars)**

Needs Category	1992 Survey	1996 Survey
Agriculture	4.2	3.8
Silviculture	2.7	3.5
Animal Feeding Ops.	3.1	2.1
Total	10.0	9.4

combustion efficiency and can reduce emissions of nitrogen by as much as 35 percent. Treatments of exhaust involve catalytic conversion, which can reduce emissions by as much as 57 percent. Additionally, there are advanced technologies being developed to provide very low and no emission vehicles.

### *Costs of Nutrient Control*

Estimating the costs of nutrient control is difficult because of the lack of comprehensive information. Site specific studies provide some insights into the relative costs of different control practices. For example, a recent assessment for the Mississippi River Basin found that the unit cost of edge-of-field N reduction techniques ranged from \$0.88 to \$5.20/kg N-loss (depending on the level of reduction), wetland restoration had a unit cost of \$6.06 to \$11.93/kg N-loss (depending on the acres of wetland restored), riparian buffers had a unit cost of \$26.03 /kg N-loss, and tertiary treatment of wastewater had a unit cost of about \$40/ kg N-loss. Cost estimates vary widely, but, in general, “high tech” measures such as wastewater and stormwater treatment are more expensive to implement than “low tech” solutions such as edge-of-field reduction measures.

The most cost effective strategy for a watershed will likely be one that combines a variety of source reduction and habitat ecosystem restoration approaches to achieve the net social optimum. In addition to reducing nitrogen inputs, there are then secondary desirable benefits of contributing to other national priorities such as the “no net loss” of wetlands, thus supporting two national mandates.

Estimating the economic costs of these approaches on a national basis is problematic because only partial information sets exist upon which to base reliable monetary estimates, and developing estimates requires a reduction target level for each estuarine system exhibiting hypoxia. A recent evaluation conducted by EPA of the cost of

controlling nonpoint pollution sources (though not specifically nutrient related, see Table 4) provides a first order estimate of the cost to the nation of controlling nutrient inputs.

### *Economic Benefits of Hypoxia Reduction*

As noted in the previous section, hypoxia in coastal waters can have a variety of impacts, ranging from effects on the fishery resources to changes in community structure and ecosystem health. Use restrictions on swimming and boating, beach closures and loss of tourism because of aesthetic and public health concerns have also been documented. There also may be significant impacts in the watershed upstream of the coastal waters due to nutrient-related degraded water quality. The most recent 305(b) Report submitted to Congress by EPA indicates that, nationally, a substantial number of river miles exhibit use impairments for aquatic life, fish consumption, and swimming and drinking water supply related to nutrient conditions.

Depending on the mix of nutrient-reduction practices implemented, environmental and economic benefits could include restored wetlands, reduced soil erosion, nutrient contamination of drinking water, waterborne human pathogens, and vulnerability to floods, enhanced wildlife habitat, and improved recreational water.

However, as with assessing the cost of nutrient control, estimating the economic benefits of reducing coastal hypoxia on a national basis is not yet feasible because there have been few comprehensive watershed studies to date. A fundamental problem is that many of the benefits to be derived from reducing hypoxia require estimating non-use values of ecosystem health, a field of economics still in an early stage of development. While several current studies and surveys such as the National Survey of Recreation and the Environment (jointly sponsored by the U.S. Forestry Service and the NOAA), will add significantly to our understanding of the value of coastal habitats, much more information is needed before a comprehensive cost/benefit assessment can be made.

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# Uncertainties and Data Gaps

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*This assessment has helped identify uncertainties in the state of our knowledge of hypoxia and eutrophication, as well as data gaps and research needed to better understand this pervasive problem. These will be instrumental in development of a national level program for further addressing nutrient issues.*

## **Uncertainties and Data Quality.**

**Symptom and Overall Assessment:** For all estuaries an analysis of data completeness and reliability for symptom data was performed so that confidence in the assessments of symptom level could be estimated. For 17 estuaries, symptom data were so limited that an assessment of overall eutrophic conditions could not be made. Most of these were on the Pacific coast. For 32 other systems, some of the symptom data provided by the experts was rated as “speculative” because it was based on spatially or temporally limited field observations. The overall confidence of symptom levels for these estuaries is assessed as low which is a reflection of either partial or unreliable data.

For greater than 80 percent of systems with high and moderate levels of overall eutrophic conditions there is a high level of confidence in the assessments, while less than half of the assessments for systems with low overall conditions are highly confident. Most assessments of low confidence are for estuaries located in the Pacific and South Atlantic regions. It is notable that estuaries with the highest level eutrophic conditions are those which have been the best studied.

**Influencing Factors:** The information and data for influencing factors was compiled from several different sources. The nutrient load estimates, based on five major sources (fertilizer, livestock wastes, point sources, atmospheric deposition, and nonagricultural sources) are from the USGS's Sparrow model. The model gives nationally comparable information, however, estimates may be biased high for large watersheds. The land use and population data used as estimators of present input and trends in input are a combination of data from the US Census Bureau and USGS Land Use and Land Cover data, each with inherent uncertainties associated with methods of estimation.

## **Data Gaps.**

The greatest need is for data that better characterizes the levels of eutrophic symptoms in estuaries, particularly for the 17 estuaries for which an overall assessment could not be made. In addition, there are 32 estuaries for which the overall assessment of eutrophic condition was made but is considered speculative due to limited or

uncertain data. Physical processes, sources and levels of nutrient inputs also need to be better characterized so that causal linkages can be made and used to develop appropriate management plans.

There is a lack of understanding of processes and mechanisms involved in the progressive development of eutrophication. For example, little is known about “thresholds,” such as the trigger points that cause toxic blooms to flourish. Additionally, a comparison should be made of the historically higher levels of biological grazing as a controlling mechanism, and the ways in which this mechanism affects the rate of development of eutrophic symptoms.

Effects of climate change, specifically global warming, and implications to water level, circulation, temperature and salinity distributions, which affect estuarine susceptibility and thus development of symptoms, also need more study. Combined effects of nutrient inputs and other pollutant stressors on the health of the estuarine ecosystem should also be investigated. All of this information should be used to develop predictive models that will enhance and ensure effective management actions now and in the future.

In addition, there is a real need for comprehensive nationally comparable information about the alternatives for reducing these problems and the costs and benefits that will result.

# Recommendations

The results of this assessment show convincingly that coastal hypoxia and other eutrophic conditions are a national problem, and that a significant influence on development of these conditions is human related nutrient inputs. Furthermore, in more than half of the estuaries studied, symptoms of eutrophication are predicted to worsen in the future if actions are not taken now to reduce present and future levels of nutrient inputs. This is a problem that demands a national level response.

## A National Response Strategy

A cooperative effort among all relevant agencies to develop a National Strategy for addressing nutrient related issues in the coastal zone should begin immediately. Within the framework of a national strategy, the information from this assessment can be used in the manner of "environmental triage" to focus management action, monitoring, and/or research on estuaries as appropriate. Different strategies should be implemented for estuaries that are:

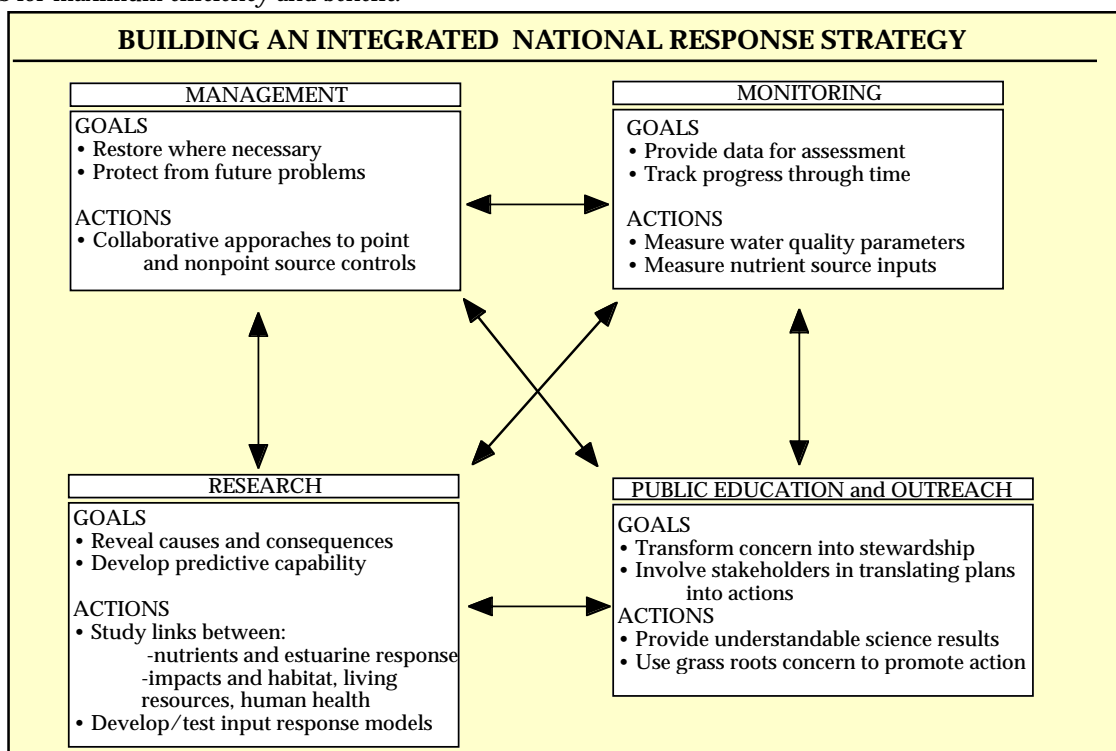
- in serious condition but can be improved with additional management effort;
  - in less serious condition but at risk of worsening;
  - in need of basic assessment because there is insufficient information for evaluation of conditions.
- A strategy for reducing eutrophic conditions should be developed integrating four lines of action that include monitoring, research, management, and public education (Figure 6).

## Management

The goals of the management component of a federal program to reduce nutrient related water quality impacts should be to restore estuarine health where necessary and to protect estuaries at risk of developing more serious problems in the future. The assessment results indicate that eutrophic symptoms are driven in large measure by human related nutrient sources and thus are problems that can very likely be improved by controlling human related inputs. For some systems there is sufficient information to take action now. However, selection of priority estuaries for management action (remediation or protection) should be based on the level of eutrophic condition, the influence of human activities, and the natural sensitivity to nutrients, to assure the most effective results.

Although point sources have been the focus of management action during the 1970s and 80s, management of non-point sources (agriculture, animal production operation, atmospheric) has gained increasing attention and should be emphasized. This report describes some of the methods and the pro-

Figure 6: Recommended national response strategy includes four interrelated components: Management, Monitoring, Research, and Public Education and Outreach. The information gained within each component is provided to each of the others for maximum efficiency and benefit.



grams that have oversight for implementation of controls. Once controls have been implemented, it is very important to track the success of management actions both for maximizing economic and ecological benefits and for use in development of predictive models. A continual evaluation of implemented controls should be made to ensure that they are successful.

Finally, these results should be used to bolster federal support and assistance to community-based, watershed-scale management efforts. It is recommended that this be done within existing programs (see Appendix 1) by encouraging federal, state, and local cooperation through state coastal zone management and national agricultural programs, and through appropriate refinements in federal laws designed to protect water quality. Specifically, current legislation and programs should be reviewed so that weaknesses can be identified and used to improve existing laws and programs. In addition, it is recommended that performance based approaches and legislation be promoted and that efforts be continued to integrate actions across all levels of government (e.g. CWAP, see Appendix 1.)

### *Monitoring*

The monitoring component of a national strategy should be implemented with two specific goals, providing sufficient information for assessment of conditions in estuaries where it is presently lacking, and tracking progress through time. This includes monitoring of symptoms within estuaries as well as changes in the amount and types of nutrient sources. In this way, implemented source controls can be evaluated and the response of the estuary can be linked directly to the success of these controls.

Due to the variety of source, it is recommended that monitoring programs be integrated across scales (local, regional, national) and across media (water, air, land). Monitoring results, including comparison of changes in input sources and response within estuarine waters, will be used to development of models to predict environmental changes associated with human activities. Monitoring results should be used to evaluate the success of management activities and encourage subsequent revisions of programs that are not working.

### *Research*

The goals of the research component should be to identify the causes and consequences of eutrophication, and to provide a basis for developing a predictive capability. This includes identification and

quantification of sources of nutrients on a watershed basis, as well as further study of the influence of physical and hydrologic characteristics on the eventual outcome of nutrient inputs. Other research should focus on the response of nutrient loadings to weather patterns, climate change, and episodic meteorological events, which effect currents and circulation and thus the fate of nutrients.

The linkage between nutrients, estuarine response, and the consequent impacts to essential fish habitat, living marine resources, and human health should be investigated, particularly the linkage between nutrients and HABs. Other questions involve eutrophication links to changes in submerged aquatic vegetation, wetlands, and macroalgae.

In addition, more research is necessary for evaluating the costs of nutrient controls and economic benefits of reducing hypoxia and other eutrophic conditions. It is recommended that nationally comparable estimates of the nonuse value of ecosystem health be made so that a comprehensive cost/benefit assessment can be developed.

Finally, like the management efforts, federal, state, municipal, and academic partnerships should be encouraged and facilitated, and efforts should be made to build on existing federal structures, academic institutions, and organizations.

### *Public Education and Outreach*

It is necessary to tie trends that cause worsening eutrophication to other issues affecting the quality of life and sustainability of communities, such as growing public concerns about sprawl and the aesthetic nature of their environment. Citizen concern should be transformed into stewardship of the estuarine environment in order to assure successful implementation of management programs to restore and protect water quality in the nation's estuaries.

It is important to encourage coastal scientists and managers to provide results to the public on a basis that is easily understood and in a way that clearly demonstrates relationships with issues of public concern, particularly explanations of the consequences of not responding. In addition there should be outreach activities directed to key constituencies (e.g., local environmental organizations, agricultural interests, extension service agents) to incorporate their involvement in and promotion of appropriate management, research, and monitoring efforts.

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# Appendix 1: Federal, State, and Local Laws and Programs

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*There are a variety of legislative and programmatic tools that can be used to control hypoxia. These range from mandatory Federal programs to voluntary local initiatives, and are described below.*

## ***Federal, State and Local Laws and Programs***

***The Clean Water Act*** - The Clean Water Act (CWA) establishes a national goal to “restore and maintain the chemical, physical, and biological integrity of the Nation’s waters.” The CWA addresses water pollution from both point sources (discrete outfalls or discharges) and nonpoint sources (runoff or diffuse pollution). Point sources are regulated through the National Pollutant Discharge Elimination System (NPDES), which establishes permit requirements that include numerical limits on the amount of pollution discharged. The Environmental Protection Agency (EPA) has delegated authority for the NPDES program to almost all of the states and, therefore, states typically administer permits for sewage treatment plants, factory outfalls, and large confined animal feeding operations. NPDES permits are based on water quality standards established by states. These standards provide an enforceable means to ensure that water pollution is reduced over time, as new standards are developed, permits are revised and discharge limits adjusted to meet clean water goals.

The CWA also addresses nonpoint or diffuse sources of pollution that originate as runoff. Section 319 of the CWA establishes a requirement that states develop and implement a statewide nonpoint source management program. Though these programs are not strictly enforceable, they include actions states will take to address a wide range of sources of polluted runoff, including agriculture, forestry, mining and urban stormwater. States receive grants from EPA to implement their programs. States are currently in the process of revising their state nonpoint source management programs to meet nine key elements identified by EPA as necessary to upgrade and improve their effectiveness. Failure to adequately address these nine key elements could result in loss of eligibility for significant increases in Federal dollars to implement section 319 programs.

Under section 303(d) of the CWA, states are required to identify and list those waters that fail to achieve water quality standards and develop total maximum daily loads (TMDLs) for those waterbodies. TMDLs establish the pollutant loads

necessary to achieve water quality standards and thereby provide a basis for further limits on pollution from both point and nonpoint sources. Development and implementation of TMDLs provides an additional tool for ensuring that water pollution loads are reduced to minimize the potential for hypoxia events.

***The Farm Bill*** - The Farm Bill establishes a variety of programs and incentives to manage agricultural activities that contribute to environmental pollution. The 1996 Farm Bill established a new Environmental Quality Incentives Program (EQIP), which provides technical, educational, and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns. EQIP is administered by the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). Working with soil and water conservation districts, states identify priority areas for focusing effort, including watersheds or other geographic regions. States can also identify significant statewide natural resource concerns (e.g., nutrient management). EQIP is implemented through conservation plans that include structural, vegetative, and land management practices. USDA/NRCS provides cost-share payments to implement practices, such as animal waste management facilities, terraces, filter strips, nutrient management, pest management, and grazing land management. Fifty percent of the funding available for EQIP is targeted to natural resource concerns related to livestock production.

The Farm Bill includes two other important programs that can reduce land-based sources of pollution – the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP). These two programs provide incentive payments to encourage farmers to convert highly erodible cropland or other environmentally sensitive acreage to vegetative cover, such as grasses, wildlife plantings, trees, filterstrips, or riparian buffers. Farmers receive an annual rental payment for land taken out of production and cost sharing is available to establish the vegetative cover practices. Establishment of riparian buffers has been shown to be an effective way to reduce nutrient pollution from

reaching adjacent surface waters, including nutrient uptake from groundwater. CRP and CREP provide a tool to establish additional buffering capacity where nutrients are contributing to hypoxia.

*The Coastal Zone Management Act* - The Coastal Zone Management Act (CZMA) establishes a Federal-state partnership for managing the Nation's coastal resources. The CZMA is administered by the National Oceanic and Atmospheric Administration (NOAA). Participation is voluntary and the program focuses on balancing competing land and water uses while protecting sensitive resources. States meet Federal requirements to gain approval of their CZM programs, after which they receive grants from NOAA for program implementation. State CZM programs offer the ability to focus on the cumulative and secondary impacts of development in coastal areas and to develop special area management plans to balance growth with resource protection.

Congress expanded the Coastal Zone Management Act (CZMA) in 1990 to include a new section 6217 entitled "Protecting Coastal Waters". Section 6217 requires that states with approved coastal zone management programs develop Coastal Nonpoint Pollution Control Programs (coastal nonpoint programs). In keeping with the successful state-federal partnership to manage and protect coastal resources achieved by the CZMA, section 6217 envisioned that nonpoint source programs developed under section 319 of the CWA would be combined with existing coastal management programs. By combining the water quality expertise of state 319 agencies with the land management expertise of coastal zone agencies, section 6217 is designed to more effectively manage nonpoint source pollution in coastal areas. Twenty-nine coastal states and territories have developed coastal nonpoint programs and are beginning to implement them. These programs include management measures for each of the major nonpoint source categories that impact coastal waters, including agriculture, forestry, urban sources, marinas, and hydromodification. Implementation of these management measures will reduce sources of nonpoint pollution that contribute to hypoxia.

*The Clean Air Act* - The Clean Air Act (CAA) regulates air emissions from area, stationary, and mobile sources. Under the CAA, EPA is authorized to establish National Ambient Air Quality Standards (NAAQS) to protect public health and

the environment. As airborne nitrogen has become an increasing concern for air deposition to surface waters, the CAA offers a tool to further control nitrogen emissions.

*The Clean Water Action Plan* - On October 18, 1997, the 25th anniversary of the Clean Water Act, Vice President Gore directed USDA and EPA to work with other federal agencies and the public to prepare an aggressive Action Plan to meet the promise of clean, safe water for all Americans. The Clean Water Action Plan (CWAP) was published in February 1998 and establishes a framework for implementing many of the existing clean water programs described above. In addition, the CWAP identified 111 "key actions" to strengthen efforts to restore and protect water resources. Several of the key actions have particular relevance for reducing inputs that lead to hypoxia:

- EPA is to publish criteria (i.e. scientific information concerning levels of a pollutant) for nutrients by the year 2000. These criteria will be used by States to develop numeric nutrient provisions of State water quality standards.
- States and tribes have worked together with the public to develop Unified Watershed Assessments, identifying those watersheds that do not meet water quality and other natural resource goals. For priority watersheds, states are now developing Watershed Restoration Action Strategies to identify the necessary actions to restore waters to their designated use, including reductions in nutrient pollution that leads to hypoxia.
- USDA and EPA have released a joint Unified National Animal Feeding Operations Strategy to minimize the environmental and public health impacts of Animal Feeding Operations.

A fundamental principle of the Clean Water Action Plan is to address water resource problems through a watershed approach, ensuring that priorities are established and actions taken in a comprehensive fashion to clean up rivers, lakes, and coastal waters.

### *State Laws and Programs*

Many state laws and programs are based on the Federal statutes and programs identified above. State water permitting and statewide nonpoint source programs are derived from the Clean Water Act, state agricultural programs are derived from the Farm Bill, and state coastal management and coastal nonpoint programs are derived from the

Coastal Zone Management Act and Coastal Zone Act Reauthorization Amendments. In addition, many states have enacted their own laws and developed state-specific programs to address particular natural resource issues. For example, Maryland's Water Quality Improvement Act was developed in response to outbreaks of *Pfiesteria piscicida* and designed to reduce nutrient pollution from agricultural sources. Oregon's Senate Bill 1010 was enacted, in part, to develop agricultural water quality management plans that will reduce impacts to salmon. These and other state initiatives provide an array of programmatic tools to further reduce sources of pollution that lead to hypoxia. In addition, many states have augmented Federal dollars with their own cost-share and grant programs to support local water pollution and watershed management initiatives.

### *Local Programs and Initiatives*

In addition to Federal and state efforts, many local governments have developed ordinances and special initiatives to reduce pollution. Most important, local governments are typically responsible for managing growth and development through planning and zoning and other land use controls. With increasing population growth and development in U.S. coastal areas posing one of the greatest threats for future coastal water quality problems, growth management and resource protection at the local level will become even more important. As with states responding to Federal mandates, local governments often implement management activities in response to state law or policy. State erosion and sediment control laws and stormwater management programs are important drivers for local urban runoff control efforts. Many local governments require site plan reviews, erosion and sediment control plans, and post-development stormwater management as conditions of approval for new construction activities. These tools are important to ensure that expanding land development does not degrade clean water or further exacerbate existing water quality problems.

## Appendix 2: On Line References

National Oceanic and Atmospheric Administration (NOAA). "Oxygen Depletion in Coastal Waters" by Nancy N. Rabalais. NOAA's State of the Coast Report.

[http://state-of-coast.noaa.gov/bulletins/html/hyp\\_09/hyp.html](http://state-of-coast.noaa.gov/bulletins/html/hyp_09/hyp.html)

A summary of dissolved oxygen depletion in US coastal waters including the national picture and case studies in Chesapeake Bay, Long Island Sound, and the Northern Gulf of Mexico.

Academy of Natural Sciences. COASTES - Estuarine Ecology.

<http://www.acnatsci.org/erd/berc/projects/coastes/coastes.html>

Explains the Complexity and Stressors in Estuarine Systems (COASTES) program which, over a six year period of study within the Patuxent River estuary, will attempt to understand the effects of environmental stressors (nutrients, inorganic toxics, dissolved oxygen) on the ecological processes of coastal ecosystems.

Chesapeake Bay Information Network. Chesapeake Bay LMER: Trophic Interactions in Estuarine Systems.

<http://www.chesapeake.org/ties/ties.html>

Provides information on the Trophic Interactions in Estuarine Systems (TIES) project, part of the Chesapeake Bay Land-Margin Ecosystems Research program, which studies secondary production within estuarine ecosystems. Includes an overview of the project, as well as some results on ichthyoplankton, mid-water trawl tows, and sediment chlorophyll-a mapping. References to publications and presentations are provided. George Mason University/Alliance for the Chesapeake Bay/Bay Journal. State-of-the-Bay: Nutrient Enrichment and Habitat Quality.

<http://web.gmu.edu/bios/bay/journal/95-04/state.htm>

Explains the causes of hypoxia and poor water quality within the Chesapeake Bay. Indicates affected areas and notes efforts at remediation.

George Mason University/Alliance for the Chesapeake Bay. 1993. Nutrients and the Chesapeake: Refining the Bay Cleanup Effort.

<http://www.acb-online.org/nutrient.htm>

Describes changes in water quality within the Bay system since colonial times. Cites excess nutrients and sediments for causing massive algal blooms that decompose and cause anoxic conditions in the Bay's central bottom waters. Explains the 1987 Bay Agreement that seeks to improve water quality within the Bay by emphasizing control and abatement of excess nutrients from all sources.

University of Maryland/Maryland Sea Grant Program. Chesapeake Bay Facts.

<http://www.mdsg.umd.edu/MDSG/CB.html>

Provides access to a summary of quick facts about the Chesapeake Bay, a map of the watershed showing drainage into the Bay, general information and research reports and papers, sponsored by Maryland Sea Grant, on the Bay's ecosystem, and links to other Internet sites providing additional information about the Chesapeake.

U.S. Environmental Protection Agency. Chesapeake Bay Program.

<http://www.chesapeakebay.net/bayprogram/pubs/87agree.htm>

Presents the 1987 Chesapeake Bay Agreement to restore and protect the Chesapeake Bay that was accepted by the states of Virginia, Maryland, Pennsylvania, the District of Columbia, the Chesapeake Bay Commission, and the Federal government.

U.S. Environmental Protection Agency. Water Quality Monitoring Data, Graphics and Analysis, Chesapeake Bay Program.

<http://www.chesapeakebay.net/bayprogram/data/wqual/wqual.htm>

Provides numerous links to data on various

physical, chemical and biological parameters measured within the Chesapeake Bay. Data for chlorophyll, salinity, dissolved oxygen, water temperature, nitrate and suspended solids are presented as figures, graphs and tables with explanations for current and past year periods. Offers on-line documents on environmental indicators of the Bay's environment and various biological, chemical, geochemical and physical parameters that have been monitored.

Gulf of Mexico Program Office. Hypoxia Conference Proceedings: List of Abstracts.

<http://www.gmpo.gov/nutrient/front.html>

Explains the Gulf of Mexico Program and the special topic of hypoxia. Presents abstracts of papers addressing the topic of hypoxia in Gulf of Mexico estuaries and coastal waters. Several abstracts provide links to the respective on-line papers.

Iowa State University. Agro-Oceanic Nutrient Flux Center.

<http://www.public.iastate.edu/~turf2surf/>

Supports a proposal to the U.S. Department of Agriculture's Fund for Rural America to establish a center where scientists, stakeholders and policy makers can create practical solutions to the hypoxia problem in the Gulf of Mexico that affects the strategic rural industries of farming and fishing. The site contains a questionnaire for stakeholders and its results, the grant proposal, and links to agriculture, hypoxia, and Fund for Rural America sites.

Rabalais, N.N. et al. 1995. Hypoxia in the Northern Gulf of Mexico: Past, Present and Future.

<http://www.gmpo.gov/nutrient/P25.PDF>

Presents information on hypoxia in the northern Gulf of Mexico, showing its distribution and dynamics (including present and historical conditions). Examines the history of hypoxia in the region as preserved in the sedimentary record. Shows changes to the ecosystem due to nutrient loading and provides a prediction of the future of the region under varying conditions of nitrogen nutrient influx.

U.S. Department of Commerce/NOAA. Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program.

<http://www.aoml.noaa.gov/ocd/necop/>

Home page of NECOP, the NOAA program to examine the effects of eutrophication by the Mississippi River on the northern Gulf of Mexico marine environment and fisheries. Data were collected between 1990 and 1996. Provides several synopses on the collection and analyses of sediment, nutrient, phytoplankton and zooplankton. Raw data collected on the cruises during this time period are also available.

U.S. Department of the Interior/Minerals Management Service. Hypoxia Publications.

<http://www.gomr.mms.gov/homepg/whatsnew/publicat/gomr/hypoxia.html>

Presents a brief list of scientific papers focusing on hypoxia in the Gulf of Mexico continental shelf area.

U.S. Environmental Protection Agency. Oxygen Depletion, or Hypoxia, in the Nearshore Gulf of Mexico off the Louisiana Coast.

<http://www.epa.gov/rgytgrnj/programs/wwpd/hypoxia.html>

Presents information on the area of hypoxic waters ("the dead zone") found in northern near-shore waters of the Gulf of Mexico along the coast of Louisiana and Texas. Gives current thinking on the reasons for the hypoxia and its effects on Gulf of Mexico fisheries. Explains the role of the Gulf of Mexico Program, a cooperative effort among federal, state and local governments.

U.S. Environmental Protection Agency. Long Island Sound Study: Hypoxia.

<http://www.epa.gov/region01/eco/lis/hypox.html>

Presents the Hypoxia section of The Comprehensive Conservation and Management Plan for Long Island Sound, approved in September 1994, addressing the problem of low dissolved oxygen

within the bottom waters of Long Island Sound and its impacts on the biota. Explains the chemical, physical, and biological synergisms leading to hypoxic conditions. Also, documents how two- and three-dimensional models of the Sound's dynamics are being used to better understand the causes of, and solutions to, hypoxia. Presents efforts by The Management Conference to ameliorate the current effects of human activities on the Sound and future plans to continue improvements.

Rutgers University. Rutgers IMC Remote Sensing Lab/New York Bight.

<http://marine.rutgers.edu/mrs/upwelling/nybintro.html>

Provides satellite map and brief discussion on upwelling along the New Jersey coastal region of the New York Bight. Indicates the mechanism by which upwelling transports nutrients inshore and leads to phytoplankton blooms that subsequently die and cause localized bottom water hypoxia/anoxia. Cites the 1976 hypoxic event and fish kill as an extreme example.

University of North Carolina at Chapel Hill/Institute of Marine Sciences. Neuse River Bloom Project Home Page.

<http://www.marine.unc.edu/groups/Paerllab/NRBP.html>

Provides information on the project's effort to study phytoplankton and nutrient interactions in the Neuse River estuary. Gives project background, objectives, sampling programs, and publications. Shows biweekly surface to bottom longitudinal (70 km) transects of oxygen and salinity for June and July 1997. It also shows longitudinal (40 km) time series profiles (1994-1996) of bottom dissolved oxygen concentrations. Times series show hypoxic and anoxic zones and areas of actual fish kills.

U.S. Department of the Interior/U.S. Geological Survey. Water Resources of North Carolina.

<http://ser1dnrcrlg.er.usgs.gov/>

Includes information on water resources (stream flow, water quality) of major riverine watersheds

within North Carolina. The "Neuse River Water Quality&ndash;Current Conditions" link gives surface and bottom water temperature, salinity, pH and dissolved oxygen (mg/l and % saturation) from three near-real-time data stations in the Neuse River. Data taken every 15 minutes for the past week are available on-line for the same three stations. Graphs of the past week's data are on-line and updated frequently. The "Neuse River Water Quality — Historic Data" link gives archival data for the watershed.

NOAA's Office of Coastal and Resources Management Coastal Zone Management

<http://www.nos.noaa.gov/ocrm/czm/welcome.html>

Provides information on the National Coastal Zone Management (CZM) Program which is a voluntary partnership between the Federal government (NOAA's OCRM) and U.S. coastal states and territories authorized by Coastal Zone Management Act of 1972 to:

Preserve, protect, develop, and where possible, restore and enhance the resources of the Nation's coastal zone and to encourage and assist in wise use of land and water resources of the coastal zone, encourage the preparation of special area management plans, and the participation, cooperation, and coordination of the public, Federal, state, local, interstate and regional agencies, and governments affecting the coastal zone.

EPA's Office of Wetlands, Oceans and Watersheds Coastal Zone Act Reauthorization Amendments Section 6217

<http://www.epa.gov/owow/nps/>

This provides information about the Coastal Nonpoint Source Pollution Control Program (Section 6217) that addresses nonpoint pollution problems in coastal waters. Section 6217 requires the 29 states and territories with approved Coastal Zone Management Programs to develop Coastal Nonpoint Pollution Control Programs. In its program, a state or territory describes how it will implement nonpoint source pollution controls, known as management measures, that conform with those described in Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. This program is administered jointly with NOAA..